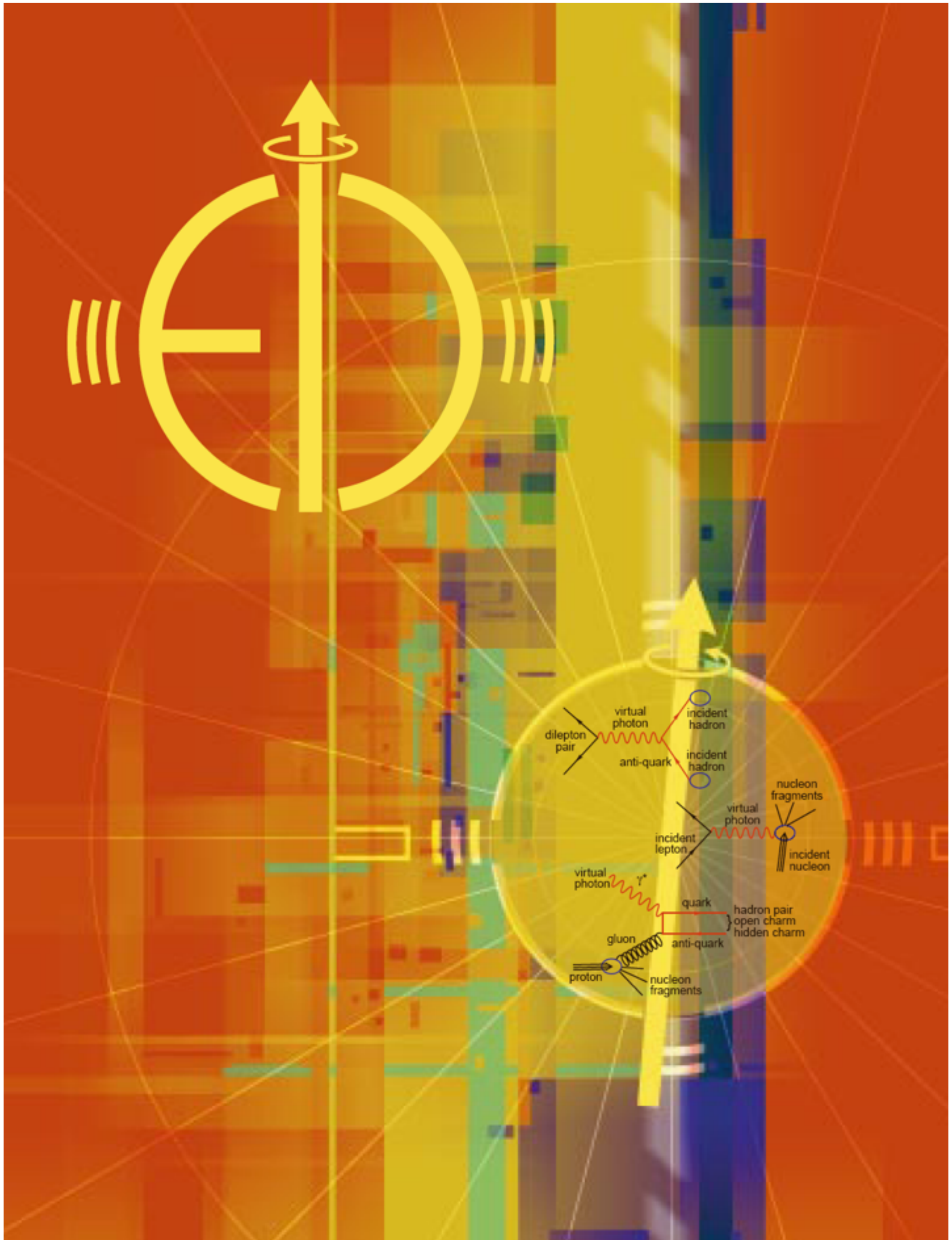


Progress Toward an Electron Ion Collider

Thomas Ullrich

BNL S&T Review

June 27, 2011

Office of Science
U.S. Department of Energy

BROOKHAVEN NATIONAL LABORATORY

The Science Case

Investigate with precision universal dynamics of elusive gluons and “sea quarks” that fundamentally make up nearly all the mass of the visible universe

EIC = High-Resolution Microscope for Gluon-Dominated Matter

Twin central themes:

- Probing the momentum-dependence of gluon densities and the onset of saturation in nucleons and nuclei
- Mapping the transverse spatial and spin distributions of partons in the gluon-dominated regime

Realization:

High $\sqrt{s}$ (~100 GeV), high L (~10^{34} cm^{-2} s^{-1}) machine, staged approach; driven by US “QCD” community

INT Workshop - Preparing the Science Case

Program “Gluons and the quark sea at high energies: distributions, polarization, tomography

- INT, University of Washington, 13 Sep to 19 Nov 2010
  - Organizers: D. Boer, M. Diehl, R. Milner, R. Venugopalan (BNL), W. Vogelsang assisted by 12 physics conveners
- articulate the theoretical motivation
- compare those goals with reality by examining the sensitivities of simulated experiments
- 128 participants (14 participants from BNL)

http://www.int.washington.edu/PROGRAMS/10-3

Successful INT Workshop

Working groups and physics conveners

*BNL

- The origin of nucleon spin ($e^{\uparrow}p^{\uparrow}$)
  - D. Hasch, M. Stratmann*, F. Yuan
- The spatial structure of QCD matter (ep, $e^{\uparrow}p^{\uparrow}$, eA)
  - M. Burkardt, V. Guzey, F. Sabatié
- QCD matter under extreme conditions (eA)
  - A. Accardi, M. Lamont*, C. Marquet
- Beyond the Standard Model / Electroweak physics (ep, $e^{\uparrow}p^{\uparrow}$)
  - K. Kumar, Y. Li*, W. Marciano*

INT Report on EIC Science Case:

- to be released June/July
- ~500 pages incl. contributions, summaries, science matrices
- input for *White Paper*

EIC White Paper

Next Milestone $\Rightarrow$ Community-wide White Paper for NSAC LRP (2012/13)

- Aimed at the wider NP community
- Lay out goals, importance and uniqueness, science matrices, golden experiment
- Steering/writing committee assembled (June 2010)
  - Overall Editors: A. Deshpande (Stony Brook), Z-E. Meziani (Temple), and J. Qiu (BNL)
  - Writers/Conveners from BNL: T. Roser, E. Aschenauer, TU

Gluon Saturation in e+A

GPD's and excl. reactions

Electroweak physics

Detector design & challenges

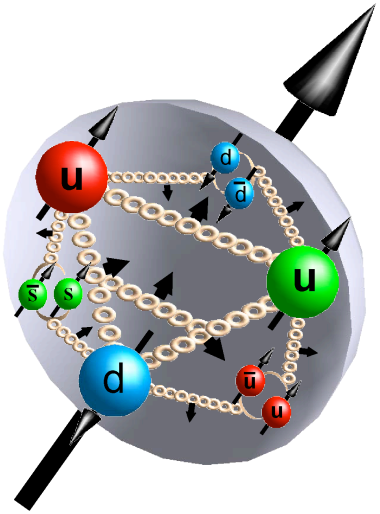
Nucleon spin structure (inclusive e+N)

TMD's and hadronization and SIDIS

Accelerator design & challenges

Example e↑p↑: Nucleon Spin Structure

Where does the proton spin come from?



Longitudinal Helicity Sum Rule:

$$\frac{1}{2}\hbar = \underbrace{\sum_q \frac{1}{2} S_q}_{\text{Total u+d+s quark spin}} + \overbrace{S_g}^{\text{Gluon spin}} + \underbrace{\sum_q L_q + L_g}_{\text{Angular momentum}}$$

(IMF only)

DSSV: D. De Florian et al. arXiv:0804.0422

	Δu_v	Δd_v	$\Delta \bar{u}$	$\Delta \bar{d}$	Δs	ΔG	$\Delta\Sigma$
DSSV	0.813	-0.458	0.036	-0.115	-0.057	-0.084	0.242

Big questions:

- $\Delta G = \int \Delta g(x)\, dx$
  - no measurements below $x \sim 5 \cdot 10^{-3}$

World Data from DIS, SIDIS, pp (incl. Hermes, Compass, RHIC)
Huge extrapolation uncertainties

Nucleon Spin Structure: Science Matrix

Science Deliverable	Basic Measurement	Uniqueness Feasibility Relevance	Requirements
spin structure at small x contribution of Δg, $\Delta\Sigma$ to spin sum rule	inclusive DIS	✔✔✔	need to reach $x=10^{-4}$ large x,Q^2 coverage about $10fb^{-1}$
full flavor separation in large x,Q^2 range strangeness, $s(x)$ - $\bar{s}(x)$ polarized sea	semi-inclusive DIS	✔✔	very similar to DIS excellent particle ID improved FFs (Belle,LHC,…)
electroweak probes of proton structure flavor separation electroweak parameters	inclusive DIS at high Q^2	✔✔ some unp. results from HERA	20x250 to 30x325 positron beam ? polarized ^{3}He beam ?

plus several other compelling measurements:

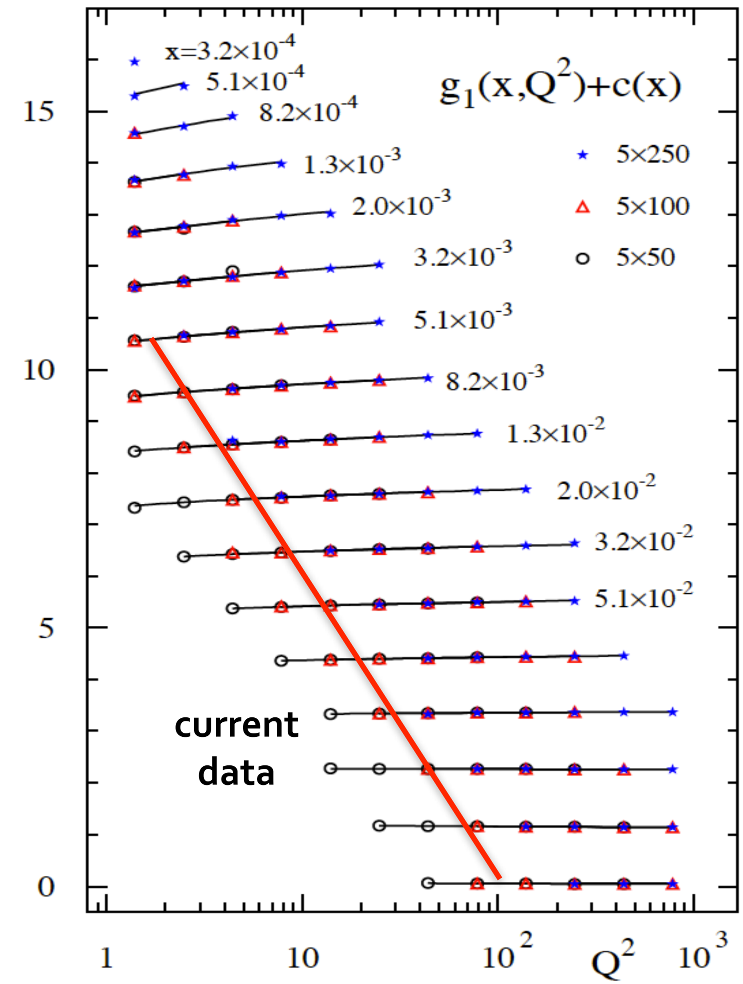
F_L , heavy flavor contributions to DIS str. fcts., photoproduction, …

Key Measurement: $\Delta g(x,Q^2)$

$$\sigma = \sigma[F_2(x,Q^2), F_L(x,Q^2),\ g_1(x,Q^2), g_2(x,Q^2)]$$

- longitudinal polarization probes mainly g_1
- g_1 has partonic interpretation like F_1 but now in terms of pol. PDFs

$$\frac{dg_1}{d\log(Q^2)} \propto -\Delta g(x,Q^2)$$



Strategy to quantify impact

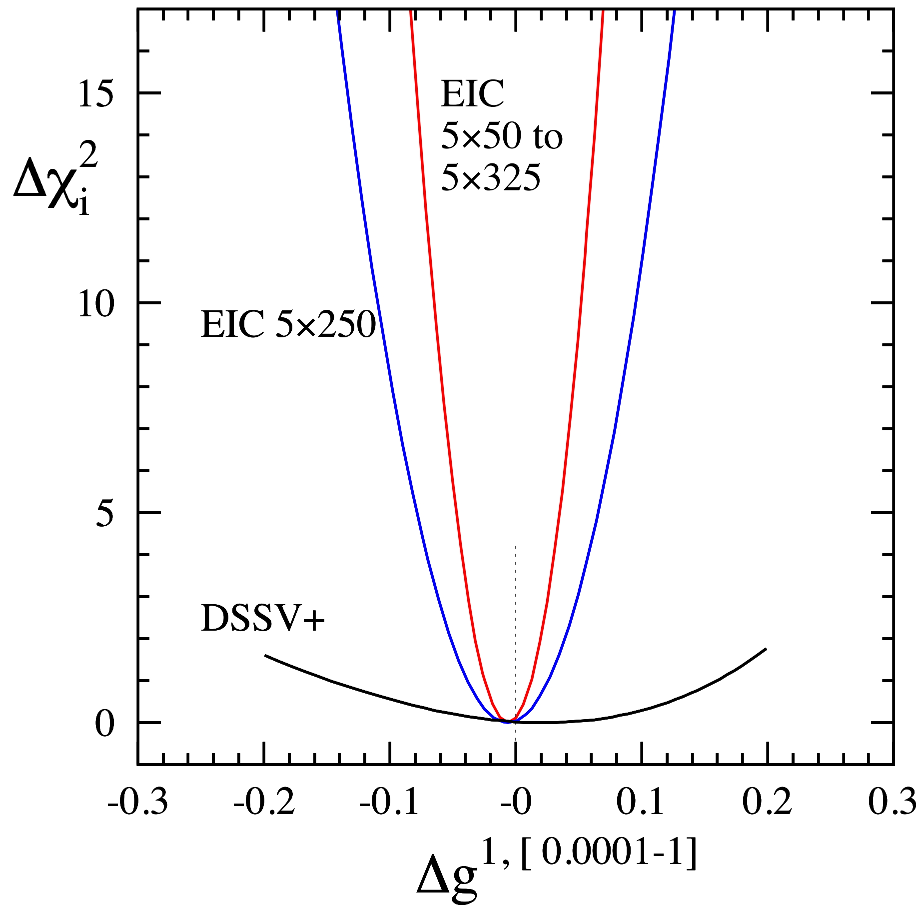
- global QCD fits with realistic pseudo-data

Polarized DIS: EIC and Impact on $\Delta g(x,Q^2)$

- 1 month running
- measurements limited by systematics
- issues: bunch-by-bunch polarimetry, relative luminosity, detector performance, radiative corrections …

Sassot, Stratmann (BNL)

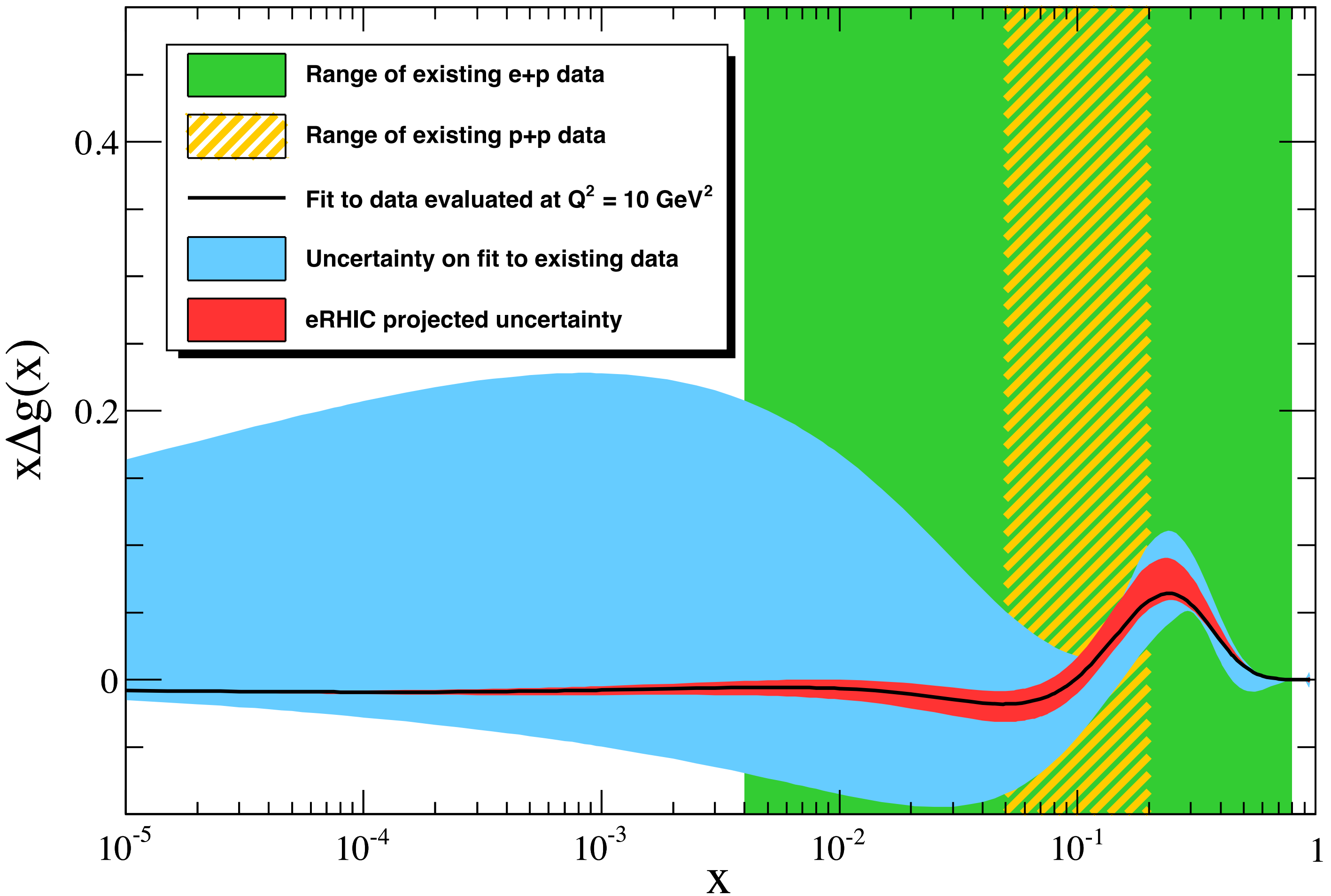
1 month of running



χ^2 profile slims down *significantly* already for lower energies (stage-1)

DSSV includes also latest COMPASS (SI)DIS data

Huge Impact of EIC on $\Delta g(x,Q^2)$

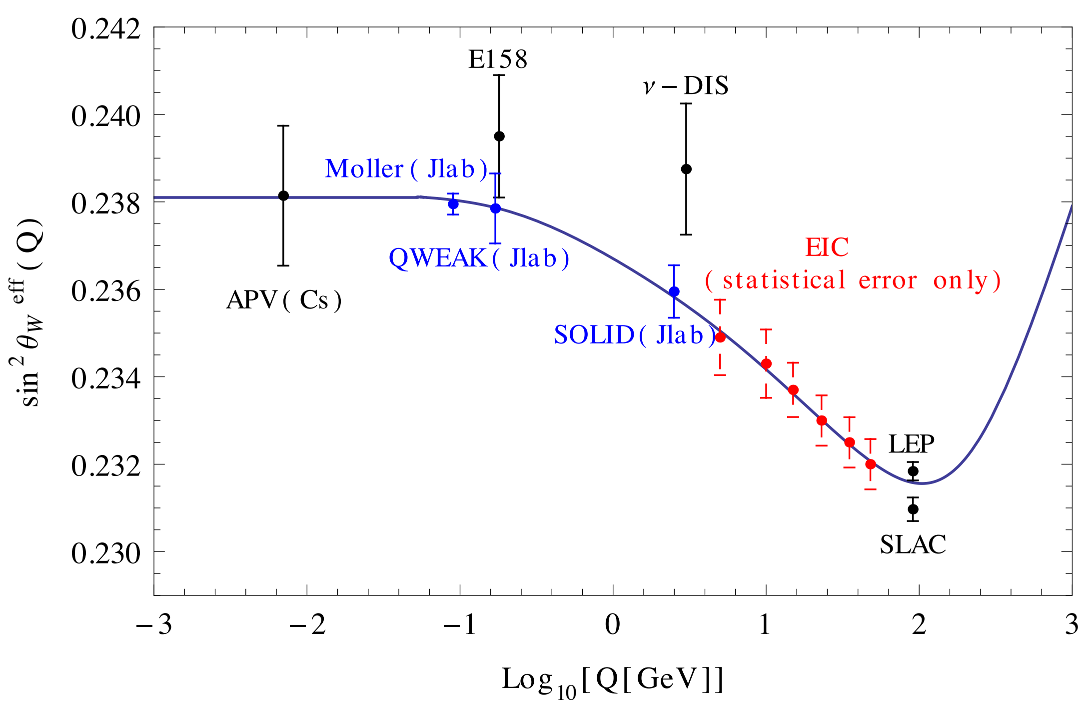


- EIC constraints ΔG down too $x \sim 10^{-3}$-10^{-4}

Electroweak Physics at an EIC

Ongoing studies at BNL:

- Lepton flavor violation (e-τ)
  - Will require $\sqrt{s} \geq 90$ GeV and $L \geq 10\ fb^{-1}$ EIC to get close or surpass HERA lepto-quark limits
- Weak mixing angle
  - measure $sin^2\theta_W$ over a wide range of Q with statistical error close to the Z-pole experiments and other planed low-Q experiments

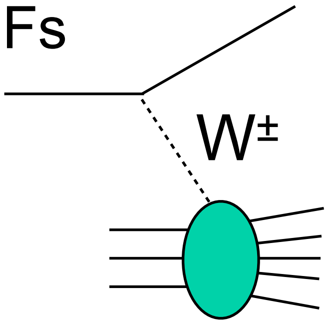


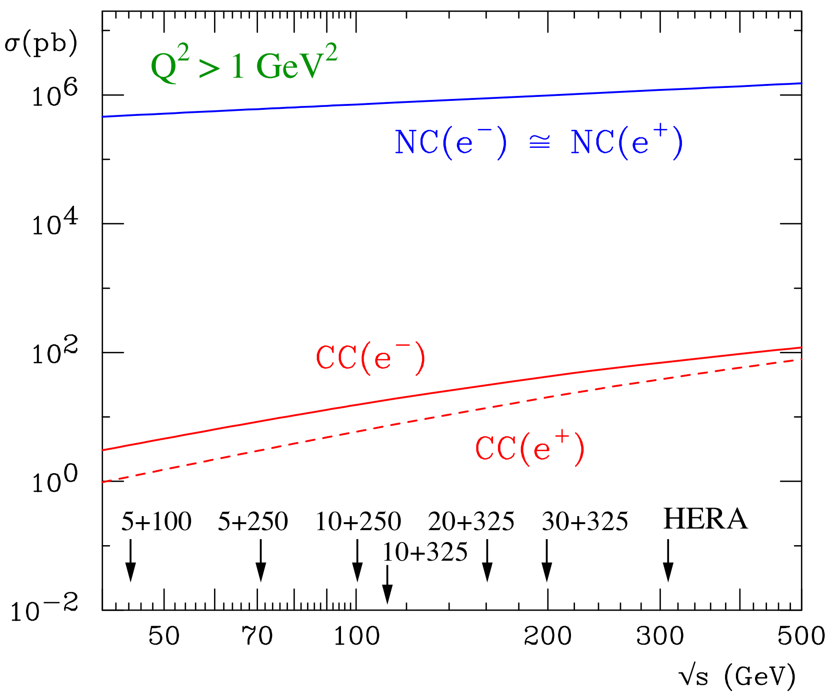
- Work in progress
  - evaluation of background
  - systematic errors
  - precision of polarization measurements?

LDRD: Marciano, Deshpande, Kumar and Vogelsang

Electroweak Structure Functions at the EIC

- At high enough Q^2 electroweak probes become important
  - lower Q^2 than Hera more than compensate by L
- New structure functions which probe combinations of PDFs different from photon exchange
  - flavor decomposition w/o SIDIS
  - unexplored so far – unique opportunity for the EIC





The difference of σ for the two nucleon helicity states:

$$\frac{d^2\Delta\sigma^i}{dxdy} \approx \frac{8\pi\alpha^2}{xyQ^2}\eta^i \left[Y_+ x g_5^i \pm Y_- x g_1^i \right]$$

CC:

$$g_1^{W^-} = (\Delta u + \Delta\bar{d} + \Delta\bar{s} + \Delta c)$$

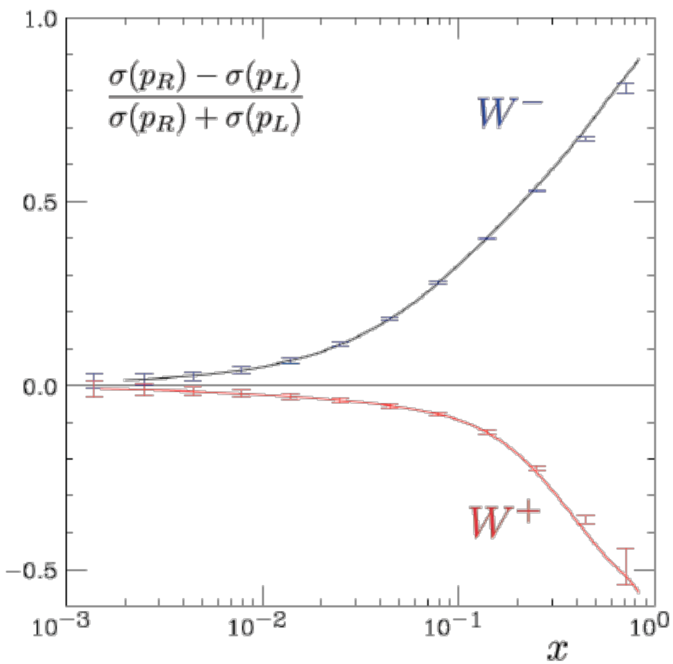
$$g_1^{W^+} = (\Delta\bar{u} + \Delta d + \Delta s + \Delta\bar{c})$$

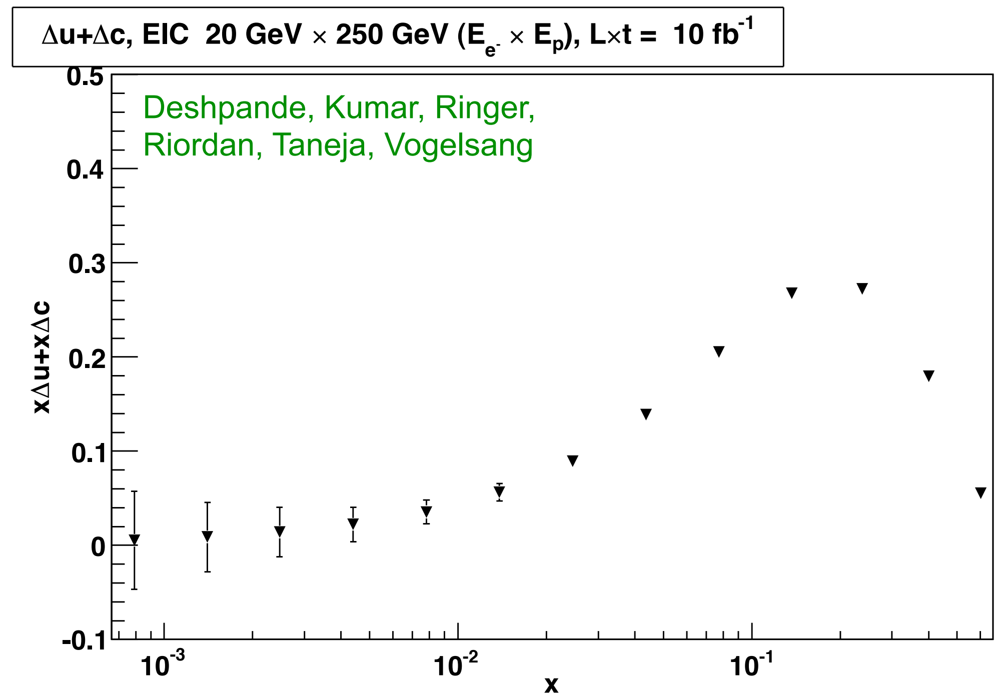
$$g_5^{W^+} = (\Delta\bar{u} - \Delta d - \Delta s + \Delta\bar{c})$$

$$g_5^{W^-} = (-\Delta u + \Delta\bar{d} + \Delta\bar{s} - \Delta c)$$

Electroweak Structure Functions at the EIC

- In CC electron scattering, e p $\rightarrow \nu_e$ X: final-state hadrons must be reconstructed to obtain x, Q^2





By measuring over a range in y, one can perform a separation of the Δu + Δc, Δd + Δs quark or anti-quark combinations.

$$A^{W^-} = \frac{(\Delta u + \Delta c) - (1-y)^2(\Delta\bar{d} + \Delta\bar{s})}{(u+c) + (1-y)^2(\bar{d}+\bar{s})}$$

$$A^{W^+} = \frac{(1-y)^2(\Delta d + \Delta s) - (\Delta\bar{u} + \Delta\bar{c})}{(1-y)^2(d+s) + (\bar{u}+\bar{c})}$$

New Regime of Hadronic Wave Function

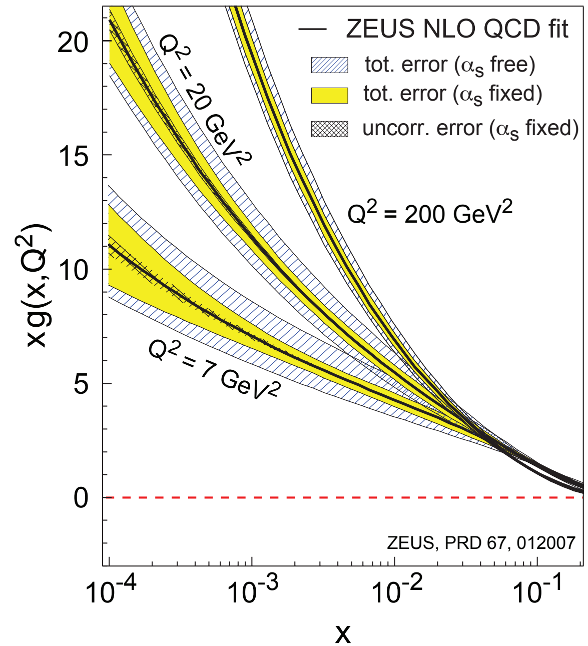
PDFs teach us that glue dominates for x < 0.1

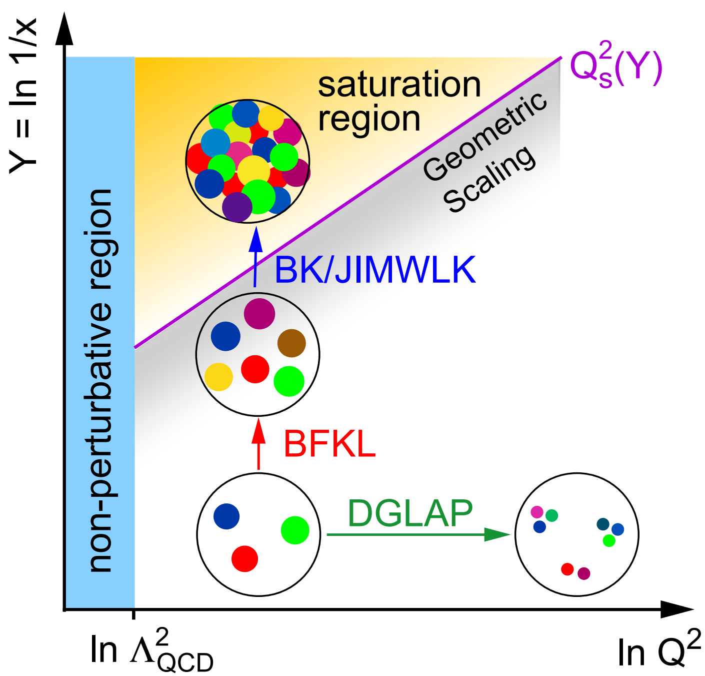
DGLAP: problems at low-Q^2

- $G(x,Q^2) < 0$ and $G(x,Q^2) < Q_{sea}(x,Q^2)$?

Gluon self-interaction has dramatic consequences:

- built in high energy "catastrophe"
  - xG rapid rise violates unitary bound

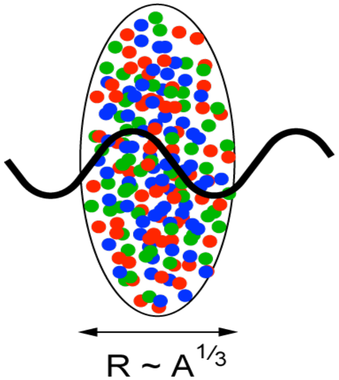




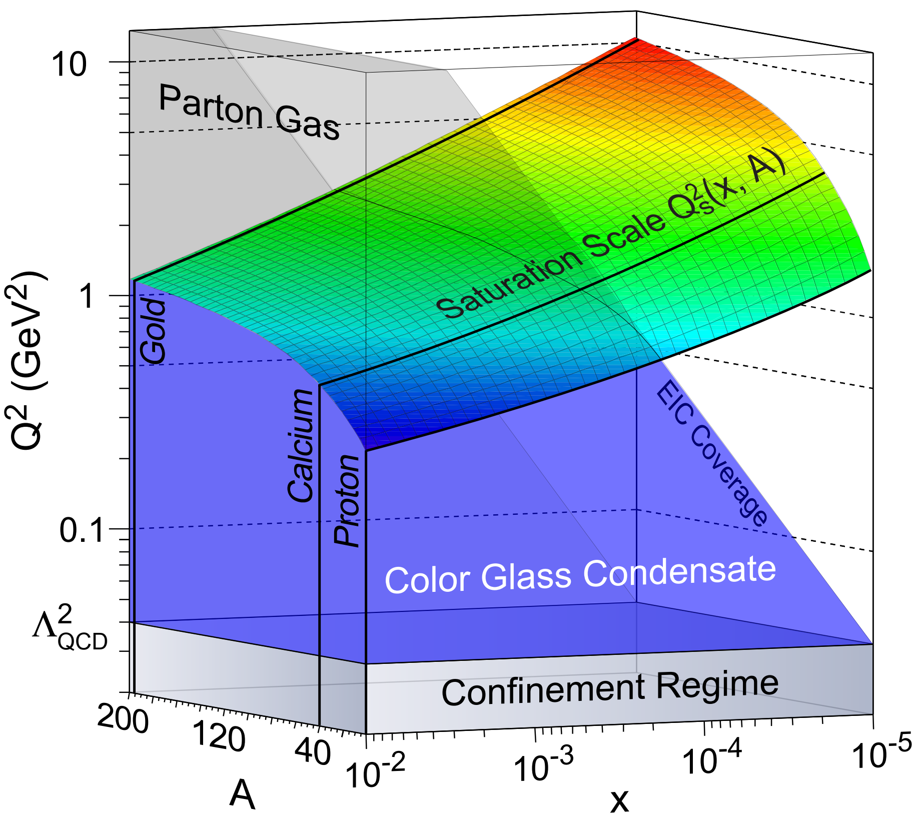
New Approach: Non-Linear Evolution

- At very high energy: recombination compensates gluon splitting
- BK/JIMWLK: non-linear effects $\Rightarrow$ saturation characterized by $Q_s(x)$
  - Describe physics at low-x & Q^2
  - Wave function is Color Glass Condensate in IMF description

Reaching the Saturation Region with e+A



$$(Q_s^A)^2 \approx cQ_0^2\left(\frac{A}{x}\right)^{1/3}$$



- Hera missed saturation regime
- Would require e+p collider at $\sqrt{s}$ > 1 TeV
- Basic Idea of e+A
  - For $L \sim (2m_N x)^{-1} > 2\ R_A \sim A^{1/3}$ probe interacts *coherently* with all nucleons
- Enhancement of Q_S with A ⇒ saturation regime reached at significantly lower energy in nuclei
  - $A^{1/3}$ only 6-7 but $x' \sim 400\ x$ for $Q = const$

Impact: EIC eA stage-1 ≈ 0.9 TeV ep (~2.5xHERA)

Gluon Saturation (e+A): Science Matrix

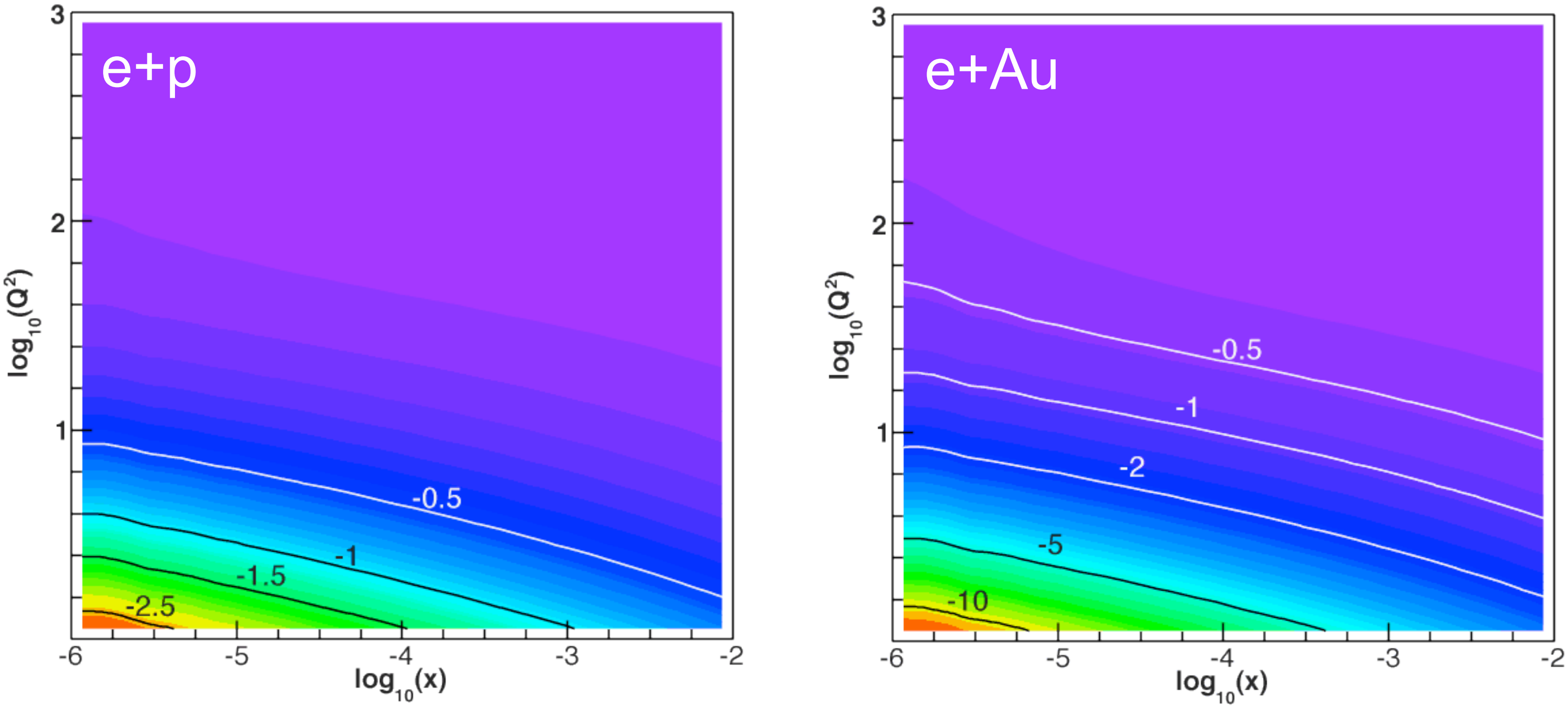
Deliverables	Observables	What we learn	Phase-I	Phase-II
integrated gluon distributions	$F_{2,L}$	nuclear wave function; saturation, Q_s	gluons at $10^{-3} < x < 1$	saturation regime
k_T dependent gluons; gluon correlations	di-hadron correlations	non-linear QCD evolution / universality	onset of saturation	measure Q_s
transport coefficients in cold matter	large-x SIDIS; jets	parton energy loss, shower evolution; energy loss mechanisms	light flavors and charm; jets	rare probes and bottom; large-x gluons

Example 1: F_L Structure Function

$F_L(x,Q^2) \sim xG(x,Q^2)$

Momentum distribution of glue

$$\text{ratio} = \frac{F_L^{\text{total}} - F_L^{\text{leading twist}}}{F_L^{\text{total}}}$$



J. Bartels, K. Golec-Biernat and L. Motyka, '11

F_L requires measurements at different $\sqrt{s}$
- wide y range

Feasibility study: $\sigma_r = F_2(x,Q^2) - y^2/Y_+ \cdot F_L(x,Q^2)$

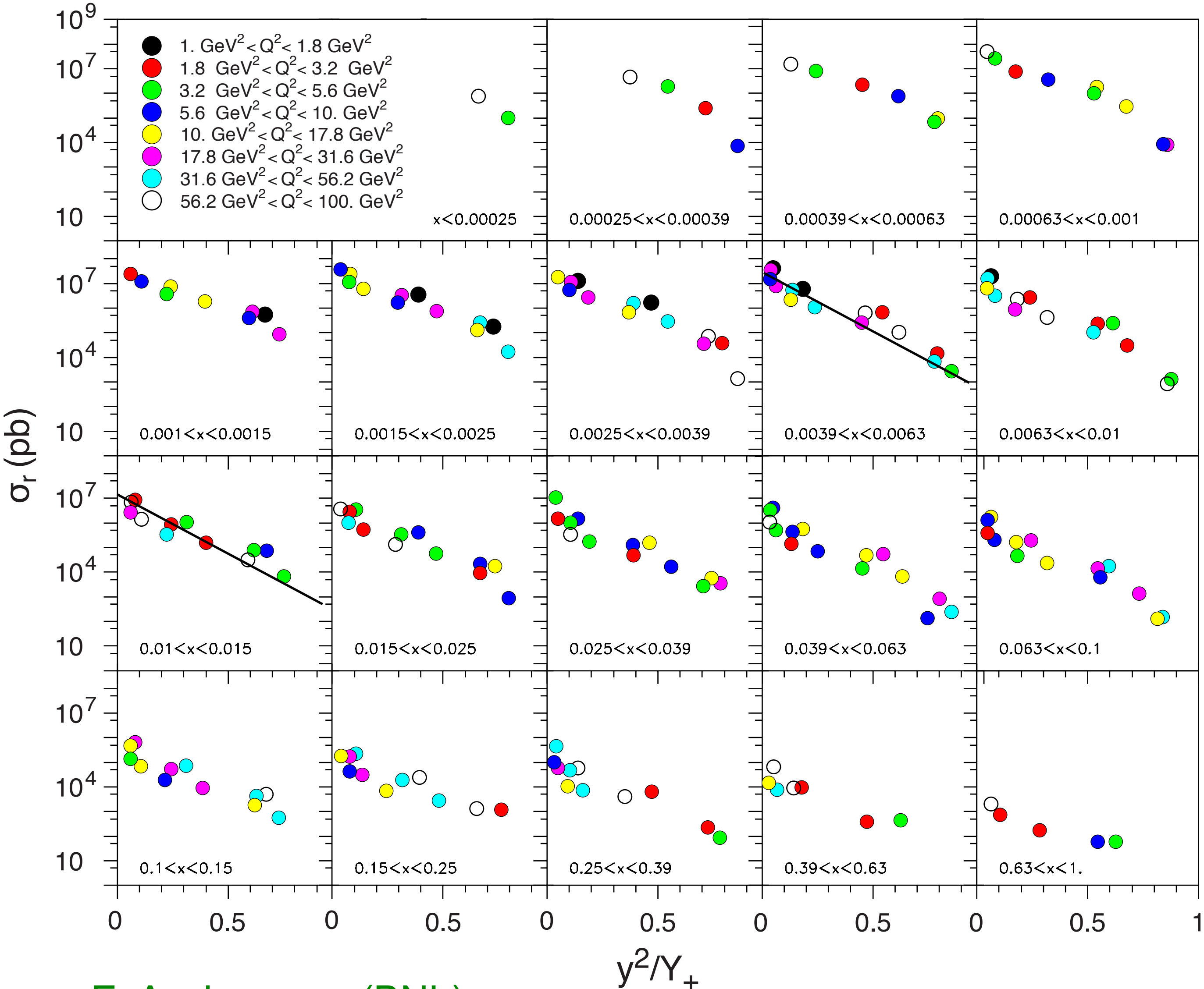
$Y_+ = 1 + (1-y)^2$

Strategies:
slope of y^2/Y_+ for different s at fixed x & Q^2

e+p:
5x50 - 5x325 running combined 4 weeks/each (50% eff)

stat. error shown and negligible

Better: Rosenbluth extraction



E. Aschenauer (BNL)

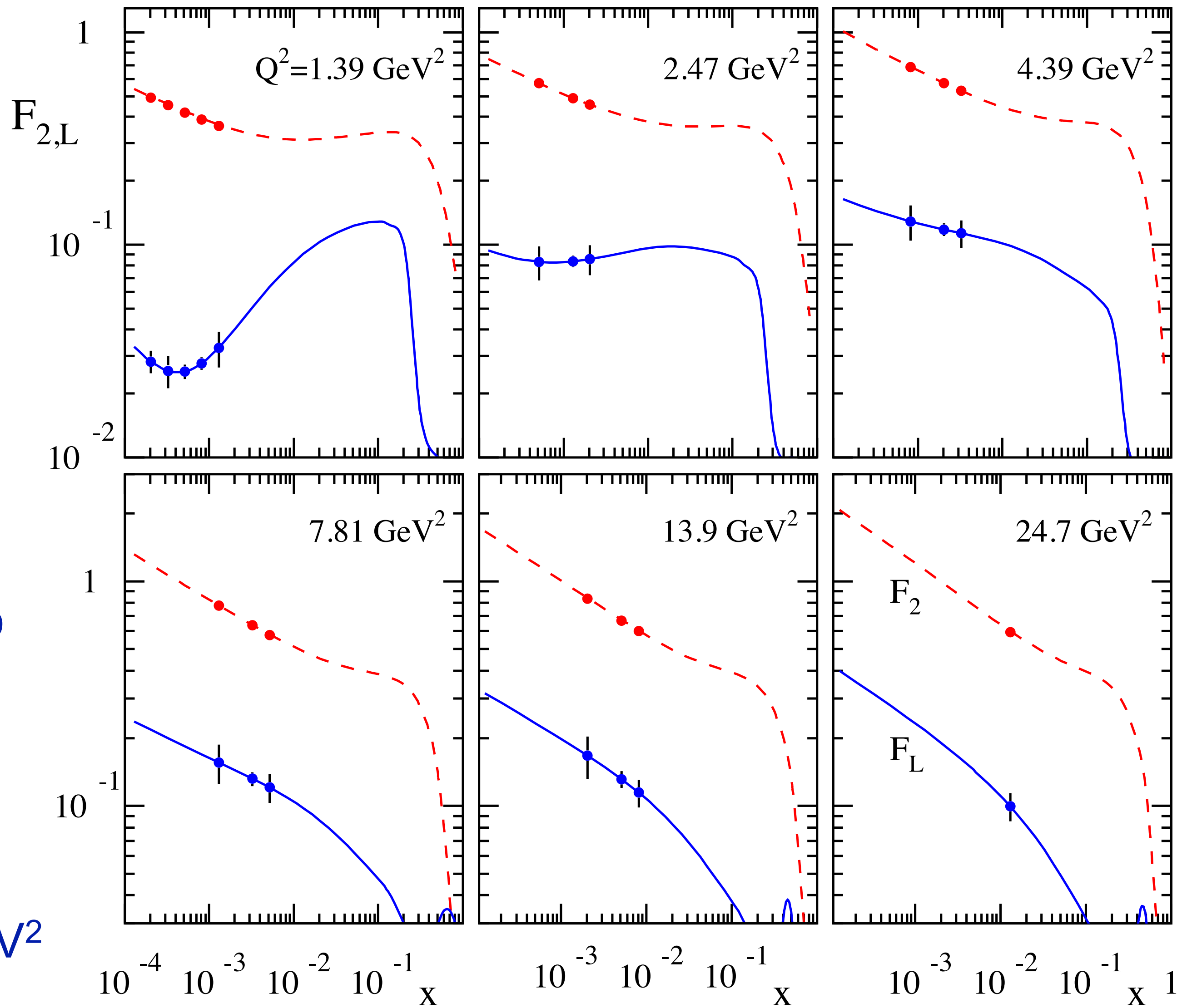
Rosenbluth Extraction of F_2 and F_L

$F_{2,L}$ extracted from pseudo-data generated for 1 month running at 3 eRHIC energies

- 5+100 GeV
- 5+250 GeV
- 5+325 GeV

Data points added to theoretical expectations from ABKM09 PDF set to visualize stat. errors

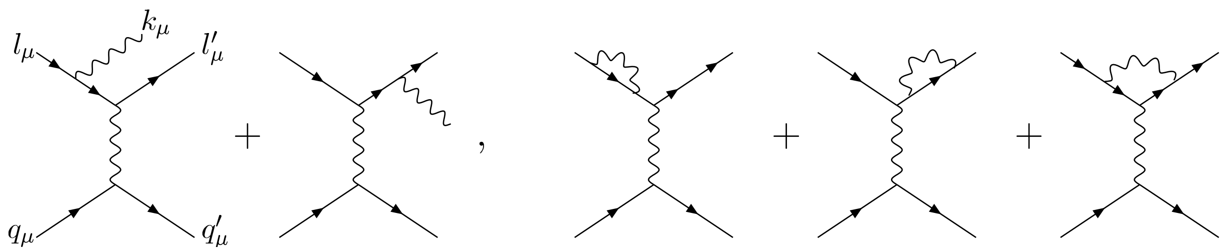
- valid for $Q^2 > 2.5$ GeV^2



Crucial for e+A: Radiative corrections

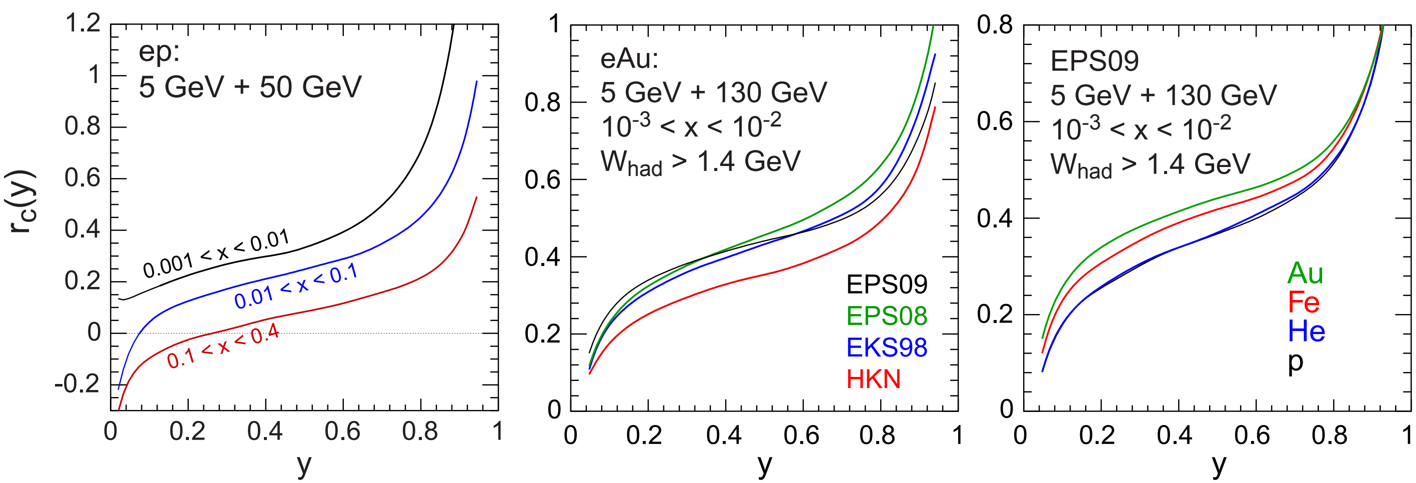
Emission of real photons =

- experimentally often not distinguished from non-radiative processes: soft photons, collinear photons



x, Q^2 extracted from e' is distorted

Correction function is fct. of y: $$r_c(y) = \frac{\mathrm{d}\sigma/\mathrm{d}y|_{O(\alpha)}}{\mathrm{d}\sigma/\mathrm{d}y|_{Born}} - 1$$



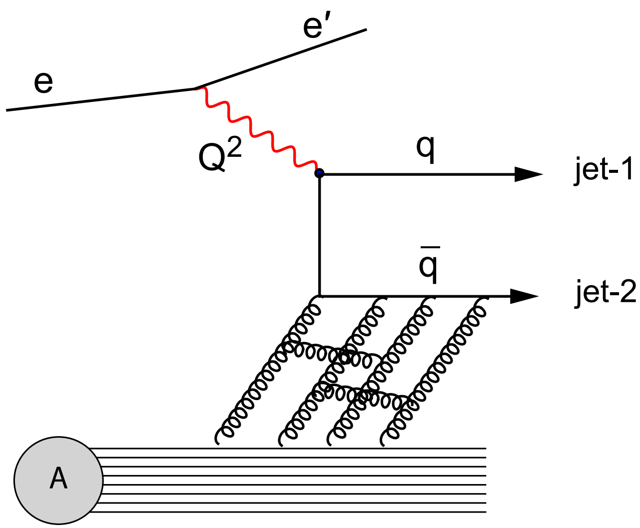
Solutions:

- cuts on W
- x, Q^2 from hadronic FS
- unfolding

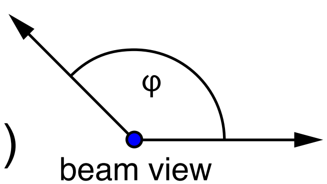
Study by Aschenauer (BNL), Stratmann (BNL) & Spiesberger (Mainz)

Example 2: Dihadron Correlations

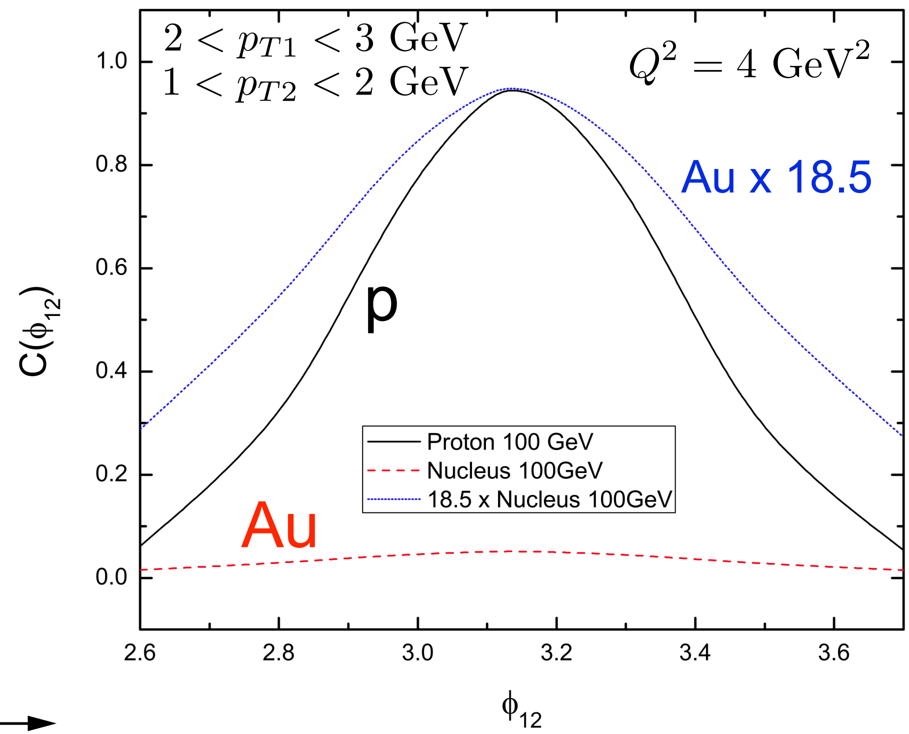
Excellent saturation signature:



Either Jets or use leading hadrons from jets (dihadrons)



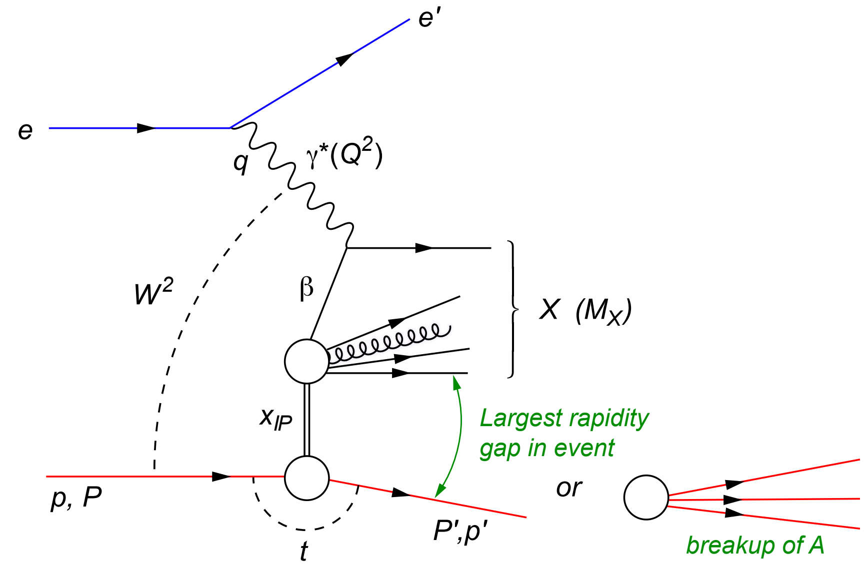
Dominguez, Xiao and Yuan (2010)



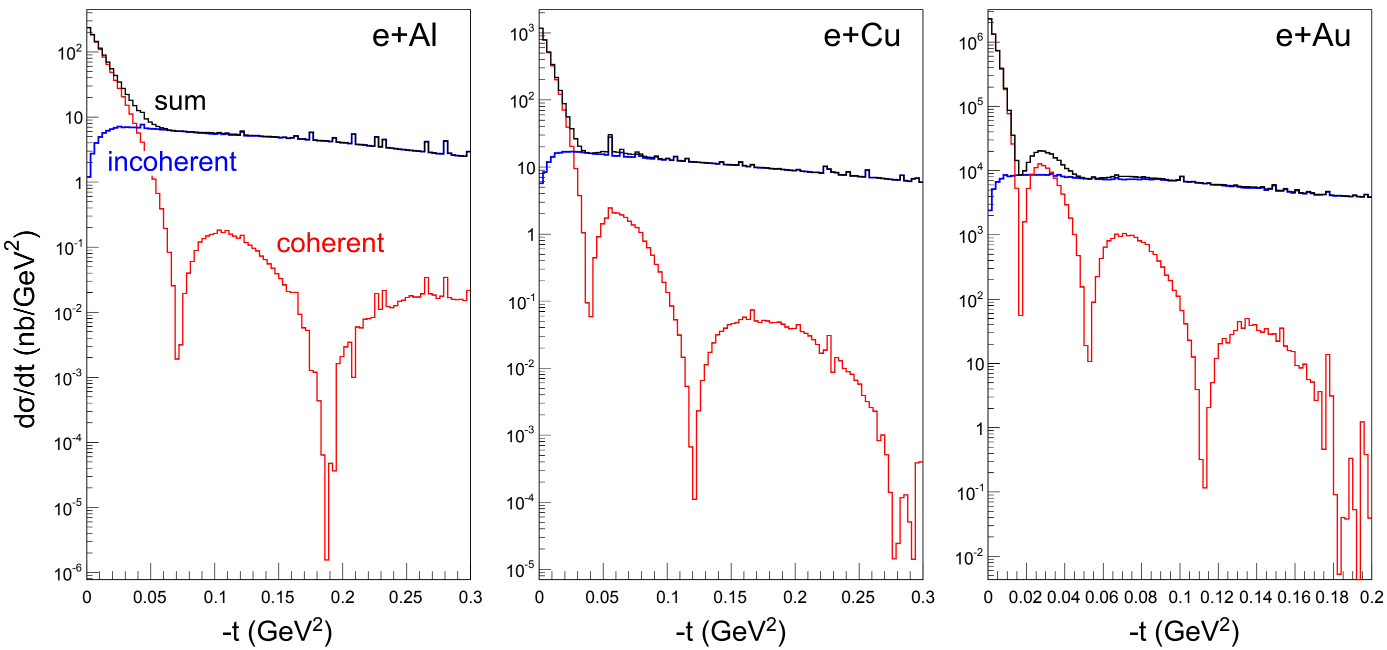
At small x, multi-gluon distributions are as important as single-gluon distributions, they contribute to such di-hadron correlations

Example 3: Diffractive Events

- Diffractive cross-section $\sigma_{diff}/\sigma_{tot}$ in e+A with saturation predicted to be ~25-40% (golden measurement)
- Process most sensitive to $xG(x,Q^2)$
- Rich physics program on momentum & spatial gluon distribution



LDRD Project (TU, T. Toll): Diff. Event Generator



$e + A \rightarrow e' + J/\psi + A'$

$d\sigma/dt$ is Fourier Transform of $\rho_{glue}(b)$

"Gluonic Form Factor"

Accelerator Design Considerations

Saturation Physics:

- low-x reach with sufficient Q^2 lever arm
- theory guidance and RHIC results $\Rightarrow$ $x = 10^{-3}$ at $Q_s^2 \sim 2$ GeV^2
- $Q_s^2 \sim A^{1/3}$
- Requires: $A \gtrsim 200$, $\sqrt{s} \sim 100$ GeV

Spin structure:

- polarized e and p beams
- flavor separation - SIDIS requires large luminosity
- electroweak probes of proton structure need large Q^2 and e^+ beams
- Requires: polarized e^-, e^+, p, He^3 (?) beams P ~ 70%, L ~ 10^{33}-10^{34} cm^{-2} s^{-1}

Electroweak Physics:

- Requires: L ≥ 10^{34} cm^{-2} s^{-1}

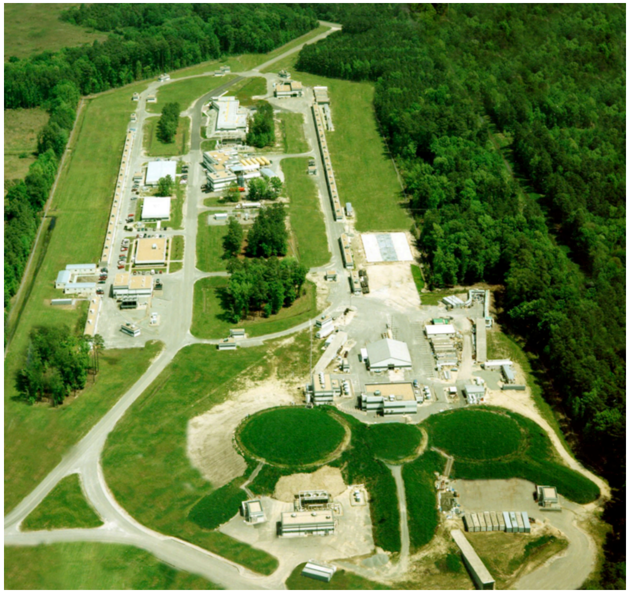
Funding considerations: Implementation in 2 stages

Two Concepts to Realize an EIC

eRHIC = RHIC +
Energy-Recovery Linac

Both designs in 2 stages

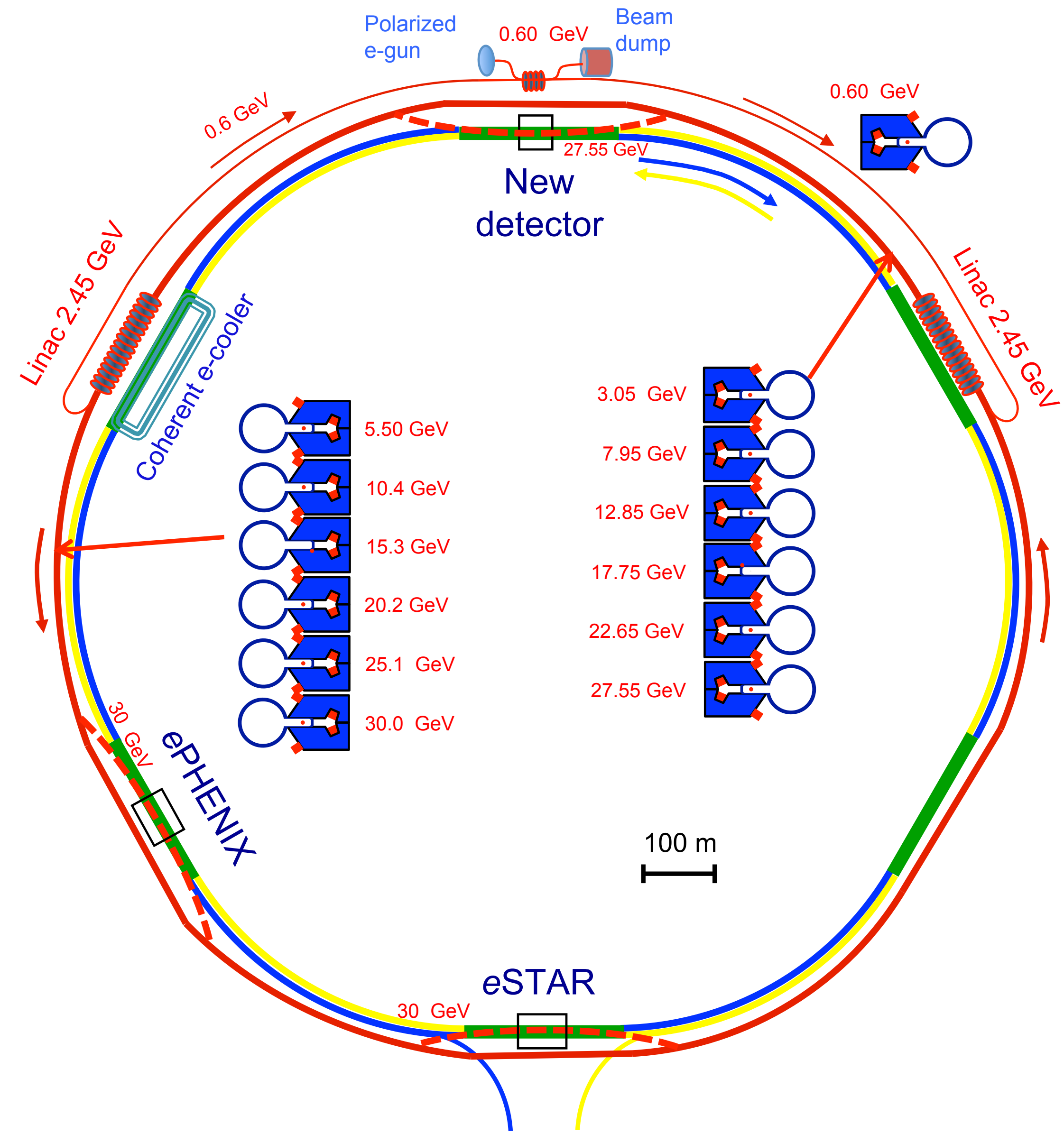
ELIC = CEBAF +
Hadron Ring



1. stage:
   - 5+100 GeV/n e+Au ($\sqrt{s}$=45)
   - 5+250 GeV e+p ($\sqrt{s}$=71)
2. stage:
   - 30+130 GeV/n e+Au ($\sqrt{s}$=125)
   - 30+325 GeV e+p ($\sqrt{s}$=197)

1. stage:
   - 11+40 GeV/n e+Au ($\sqrt{s}$=42)
   - 11+100 GeV e+p ($\sqrt{s}$=66)
2. stage:
   - 20+100 GeV/n e+Au ($\sqrt{s}$=89)
   - 20+250 GeV e+p ($\sqrt{s}$=141)

eRHIC Overall Concept



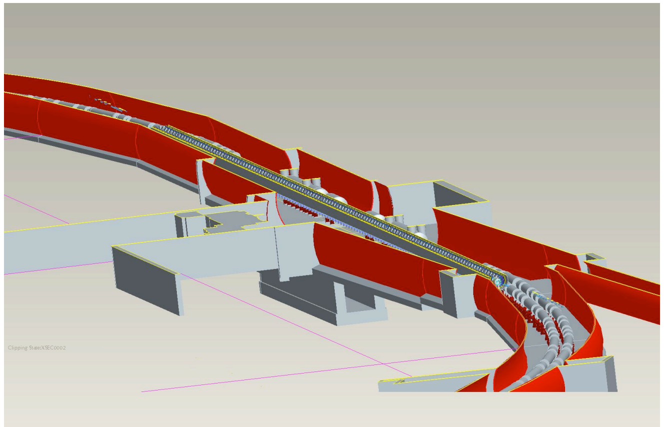
2 Energy Recovery Linacs

6 recirculating passes

Staging by increasing linac length

Installed within RHIC tunnel

⇒ lower cost



R&D ERL under construction

Aim: 0.5 amp CW

D. Kayran, G. McIntyre

See talk by T. Roser

eRHIC Luminosities

Reaching high luminosity:

- high average electron current (50 mA = 3.5 nC * 14 MHz)
  - energy recovery linacs; SRF technology
  - high current polarized electron source
- Coherent electron cooling of hadron beams
- β*=5 cm IR with crab-crossing

L in 10^{33} cm^{-2} sec^{-1}

		p and p↑				Au *L in ep equiv.*			
	E/GeV	100	130	250	325	50	75	100	130
e	5	0.62 (3.1)	1.4 (5)	9.7	15	2.5	8.3	11.4	18
	10	0.62 (3.1)	1.4 (5)	9.7	15	2.5	8.3	11.4	18
	20	0.62 (3.1)	1.4	9.7	15	0.49	1.7	3.9	8.6
	30	0.12	0.28	1.9	3	0.1	0.34	0.77	1.7

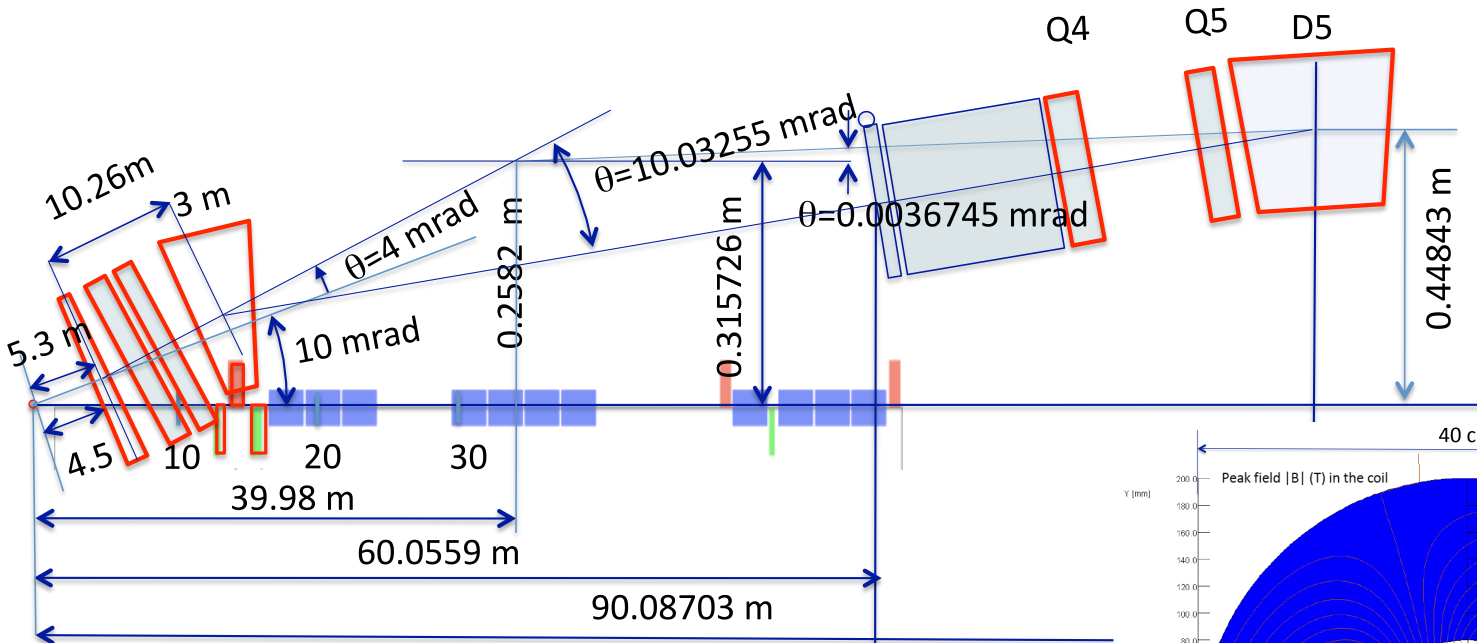
Interaction Region Design

Lessons from Hera

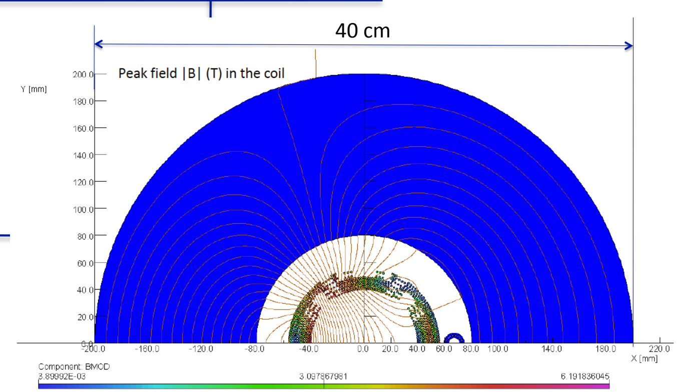
- Avoid bending electrons to avoid synchrotron radiation problems
- IR design with 10 mrad crossing angle using the crab cavities

Intensive discussions between EIC Task Force and eRHIC designers

- Neutron detection (ZDC) with a solid angle of 8 mrad
- Allow room for forward detectors



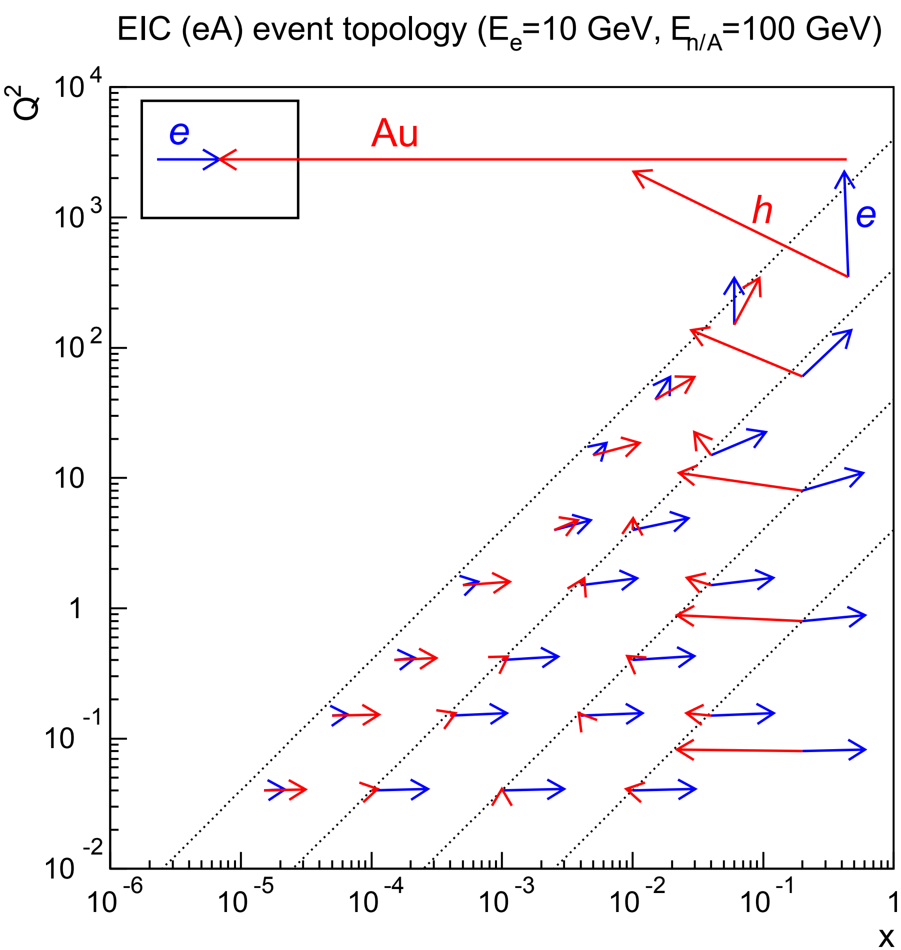
Dejan Trbojevic (CAD)



Brett Parker (CAD)

Detector Design Considerations

- Acceptance changes as √s increases
  - √s ↗ ⇒ θ(e, beam axis) ↘



Inclusive DIS:

- High Q^2 events go into central detector
- Low Q^2 events have small scattering angle

Semi-Inclusive DIS:

- hadrons go from very forward to even backward

Exclusive Reactions:

- decay products from excl. ρ, φ, *J*/ψ go from very forward to central to backward

Detector Design Considerations

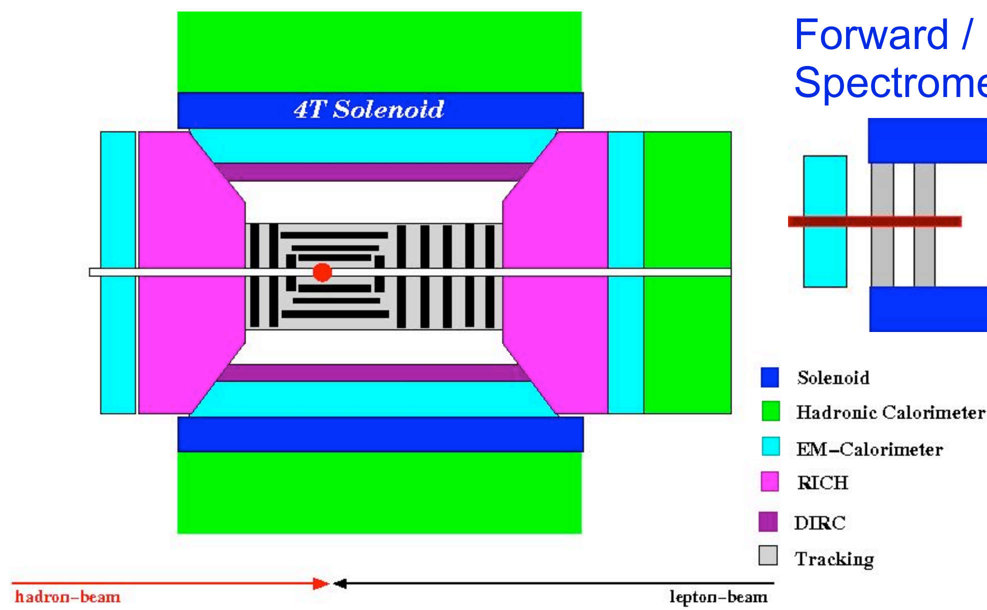
	Exclusive /diffractive reactions ep/A → e'p'/A'VM	Semi-inclusive reactions ep/A → e'πX	Inclusive reactions ep/A → e'X	Electro-weak reactions
4π acceptance	✔	✔		
Excellent electron identification			✔	✔
Nuclear breakup detection	✔			
Good jet identification		✔		
Hadron PID	✔	✔		✔
Detect outgoing scattered proton	✔			
Detect very low Q^2 electron	✔		✔	
High demands on momentum and/or energy resolution	✔		✔	
good (secondary) vertex resolution		✔	✔	

Detector Concepts

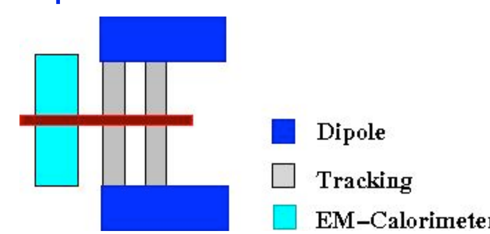
- Feasibility of using PHENIX and/or STAR for 1st stage is currently studied (see talks by N. Xu & B. Jacak)
- New detector
  - technical challenging & expensive
  - considering staged option
- Detector studies underway
  - Geant4 & Fluka in progress (T. Burton, M. Baker)
  - tightly related to R&D projects (see talk by T. Ludlam)

Emerging concept:

- High acceptance $-5 < \eta < 5$ central detector with low material tracker
- Very forward electron and proton detection, may be dipole spectrometers



Forward / Backward Spectrometers:



EIC Efforts at BNL (I)

EIC Task Force:

- Physics case, simulations, detector design
- Co-chairs: E. Aschenauer (Spin/PHENIX), TU (STAR)
- Active Members:
  - T. Burton* (TF) - TMDs, detector
  - S. Fazio* (TF) - DVCS, GPDs
  - T. Toll* (LDRD TU) - e+A event generator
  - M. Lamont (STAR/EIC) - software & jets
  - J.H. Lee (STAR/EIC) - diffraction, roman pots, di-hadrons
  - W. Guryn (STAR/EIC) - roman pots
  - R. Debbe (STAR/EIC) - F_L
  - Liang Zheng* (student Wuhan/sup. Lee) - dihadrons
  - M. Baker - TMD & Geant4
- Close collaboration with theory
  - R. Venugopalan (eA), M. Stratmann (ep), J. Qiu (ep), Z. Kang
- Close collaboration with CAD
  - V. Litvinenko (eRHIC), V. Ptitsyn (eRHIC), D. Trbojevic (IR), J. Beebe-Wang (Synch. Rad.)

*100% EIC

EIC Efforts at BNL (II)

Close collaboration with RHIC experiments

- eSTAR working group: chair Z. Xu (BNL) & E. Sichtermann (LBL)
- ePHENIX: E. Aschenauer, A. Deshpande

Successful Summer Student Program

- 2010: 5 summer students working on detector & acceptance studies for various processes
- 2011: 3 summer students to continue efforts

Meetings

- eRHIC Steering Group - biweekly
- EIC Task Force - weekly (open meeting)
- EIC Collaboration - participate in collaboration meetings

Web sites

- EIC Task Force: https://wiki.bnl.gov/eic/
- CAD eRHIC: http://www.bnl.gov/cad/eRhic/

EIC Efforts at BNL (III)

Moderate manpower level can only succeed with an intensive visitor & travel (expert) program:

Janusz Chwastowski	3/7/11 - 3/14/11	Lumi monitoring
Markus Diehl	6/28/10 - 8/28/10	All aspects of EIC
Henri Kowalski	3/23/10 - 6/15/10	ep/eA
Alexei Prokudin	12/15/10 - 12/17/10	TMDs
Felix Sefkow	12/13/10 - 12/15/10	Calorimetry
Hubert Spiesberger	3/23/11 - 4/7/11	Radiative correction
Tuomas Lappi	3/12/11 - 3/18/11	eA - Diffraction
Will Horowitz	6/20/10 - 6/30/10	eA - Diffraction
Cyrille Marquet	4/15/11-4/19/11	eA - Saturation
Dieter Mueller	???	GPDs

Future: Javier Albacete, Bob Charity, Paul Newman, Rodolfo Sassot, Dieter Mueller, Agnieszka Luszczak

IAC Advisory Committee

International Advisory Committee for the EIC

- Put in place by BNL & JLAB directorate
- Members from NP & HEP community and machine experts
  - Joachim Bartels (Hamburg), Allen Caldwell (Munich), Albert De Roeck (CERN), Rodney Gerig (ANL), Walter Henning (ANL) [chair], David Hertzog (U. Illinois), Xiangdong Ji (Maryland), Robert Klanner (DESY) , Al Mueller (Columbia) , Sergei Nagaitsev (FNAL) ,Naohito Saito (JPARC) ,Robert Tribble, Uli Wienands (SLAC) ,Vladimir Shiltsev (FNAL)
- Last Meeting at JLab, April 10, 2011

IAC Remarks and Recommendations

Note: no written version yet, here notes from close-out

- Committee finds substantial progress on all fronts and was happy to see a large overlap of machine parameters between the two designs being proposed (ELIC and eRHIC).
- Accelerator experts in the committee see timelines of some of the new machine developments as a challenge (e.g. Coherent Electron Cooling)
  - Q: What is the impact if the luminosity achievable were 5 x 10^{32} cm^{-2} s^{-1} (at stage-1) and few times 10^{33} at a later date?
- The committee suggests that the two machine proposal be reviewed by external accelerator experts not too late in the future.
- Given that the realization of the EIC will take some time:
  - Q: Which of the open questions in QCD will still be compelling as they are now? Which might be at least in parts answered by the LHC?

Summary

- Significant EIC efforts at BNL
  - Task Force:
    - physics case (e↑p↑, eA), detector design efforts, feasibility studies
    - close collaboration with NP theory & CAD
    - impact only possible through strong visitor & LDRD program
  - CAD
    - machine & IR design almost complete, R&D ongoing
    - eRHIC technical design report in August, cost review end 2011
- Very successful INT workshop on EIC physics case
  - INT report on EIC Science Case June/July
- White Paper - end 2011